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NPS SOLAR CELL ARRAY TESTER CUBESAT FLIGHT TESTING AND INTEGRATION

by

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September 2014

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The Naval Postgraduate School Solar Cell Array Tester (NPS-SCAT) is the first CubeSat for the Naval Postgraduate School (NPS). The NPS-SCAT mission was designed to measure solar cell performance degradation in low earth orbit. NPS-SCAT serves as a pathfinder for future NPS CubeSat missions. This thesis documents the pre-flight NPS-SCAT battery analysis, power budget, vibration analysis, beacon antenna integration evaluation, and conformal coat study. Some data from the flight is presented, which validates the pre-flight power budget analysis.

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NPS SOLAR CELL ARRAY TESTER CUBESAT FLIGHT TESTING AND INTEGRATION

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ABSTRACT

The Naval Postgraduate School Solar Cell Array Tester (NPS-SCAT) is the first CubeSat for the Naval Postgraduate School (NPS). The NPS-SCAT mission was designed to measure solar cell performance degradation in low earth orbit. NPS-SCAT serves as a pathfinder for future NPS CubeSat missions. This thesis documents the pre-flight NPS-SCAT battery analysis, power budget, vibration analysis, beacon antenna integration evaluation, and conformal coat study. Some data from the flight is presented, which validates the pre-flight power budget analysis.

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LIST OF ACRONYMS AND ABBREVIATIONS

1U	one unit CubeSat
B/U	backup
BTJM	triple-junction with monolithic diode
C&DH	command and data handling
CERTO	coherent electromagnetic radio tomography
CONOPS	concept of operations
COTS	commercial-off-the-shelf
CTFP	configurable fault tolerant processor
CubeSat	cube satellite
DOC	depth of charge
DOD	depth of discharge
EDU	engineering design unit
ELaNa	Experimental Launch for Nanosatellites
EPS	electrical power subsystem
ESP	experimental solar panel
GEVS	General Environmental Verification Standard
I2C	inter-integrated circuit
ISS	International Space Station
ITJ	improved triple junction
LEO	low earth orbit
MEMS	mirco-electromechanical systems
MOSFET	metal-oxide-semiconductor field-effect transistor
NiChrome	nickel-chromium
NPS	Naval Postgraduate School
NPSAT1	NPS Spacecraft Architecture and Technology Demonstration Satellite
NPS-SCAT	NPS Solar Cell Array Tester
ORS	operationally responsive space
SMS	solar cell measurement system
SOC	state of charge
TACS	triangular advanced solar cell

UHF	ultra-high frequency
UTJ	ultra triple junction
W-hr	watt-hour

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I. INTRODUCTION

A. HISTORY AND MISSION OF NPS-SCAT

The Naval Postgraduate School Solar Cell Array Tester (NPS-SCAT) is the first one unit CubeSat (1U) to be built at the Naval Postgraduate School (NPS). The 1U CubeSat is an industry standard and is defined as a satellite that measures 10cm x 10cm x 10cm with a mass no greater than 1.33kg [1]. CubeSats have become very popular as an option for education purposes because of the simplicity of the technology and the ease of availability. They are rapidly becoming useful for real scientific and national objectives as well.

1. NPS-SCAT from NPSAT1

NPS-SCAT is based on a single experiment from the NPS Spacecraft Architecture and Technology Demonstration Satellite 1 (NPSAT1). The NPSAT1 program has several payloads, including a configurable fault tolerant processor (CFTP), a micro-electromechanical systems (MEMS) rate sensor, a commercial-off-the-shelf (COTS) camera, a coherent electromagnetic radio tomography (CERTO) beacon, Langmuir probe, and a solar cell measurement system (SMS) [2]. NPSAT1 has experienced delays due to its complexity and the limited availability of students. Therefore, it was decided to take a single NPSAT1 experiment and implement it in the CubeSat form factor, leading to the development of NPS-SCAT as a pathfinder for the educational use of CubeSats at NPS. NPSAT1 (shown in Figure 1) is currently scheduled for a launch in 2016.

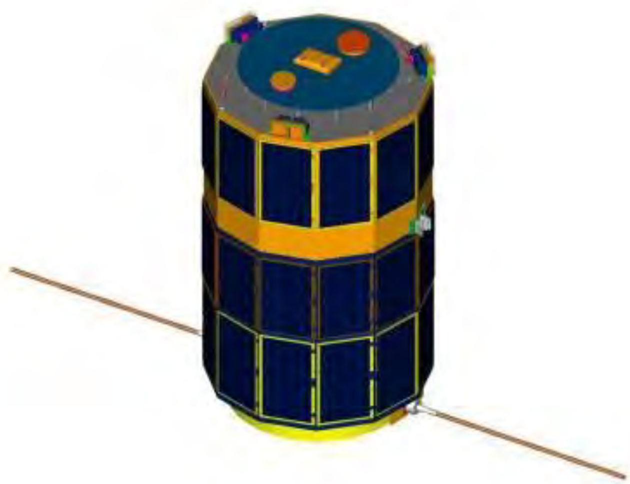

Figure 1. NPSAT1, from [3]

The lifecycle costs for a CubeSat are expected to be smaller than that of a larger, more complex satellite. The design cycle is shorter and time from concept to launch should also be shorter, as the complexity of the satellite typically drives the budget and the schedule. Given the relative simplicity of a solar cell testing satellite, NPS-SCAT utilizes a commercial-off-the-shelf (COTS) 1U CubeSat structure and as much other COTS hardware and software as possible, enabling the students to focus on developing the payload and performing the integration and testing of the systems.

2. Mission of NPS-SCAT

The mission of NPS-SCAT is to measure the degradation of solar cells in low earth orbit (LEO). NPS-SCAT, shown in Figure 2, will also demonstrate the use of the CubeSat as a test bed for future experiments. The flight, using NPS-developed solar cell panels, will validate the NPS-SCAT power analysis and demonstrate how to provide adequate power for future payloads.

Figure 2. Fully Integrated NPS-SCAT

It is the goal of the NPS CubeSat program to have a standard CubeSat bus to shorten the development lifecycle to something that can be done on in two or less years, the approximate time in residence for a student at NPS. The standard bus would use the Pumpkin FM430 board, the ClydeSpace Electrical Power Subsystem (EPS) and battery, the MHX-2400 radio, and the Pumpkin CubeSat structure. This standard bus would allow for different experiments. NPS-SCAT, shown in Figure 2, uses the standard bus systems described above. Additionally, a solar measurement system (SMS) board and solar power panels were developed at NPS and added to the bus. An ultra-high frequency (UHF) communications board, called the beacon board, was added in collaboration between NPS and the California Polytechnical University (Cal Poly). Although, many of the details of NPS-SCAT have been discussed in previous thesis work (such as [4]), some of the systems are briefly covered here to appropriately orient the reader to the satellite.

Figure 3 shows a schematic of the four boards in NPS-SCAT; the SMS, the beacon board, the EPS and battery, and the FM430 and MHX-2400.

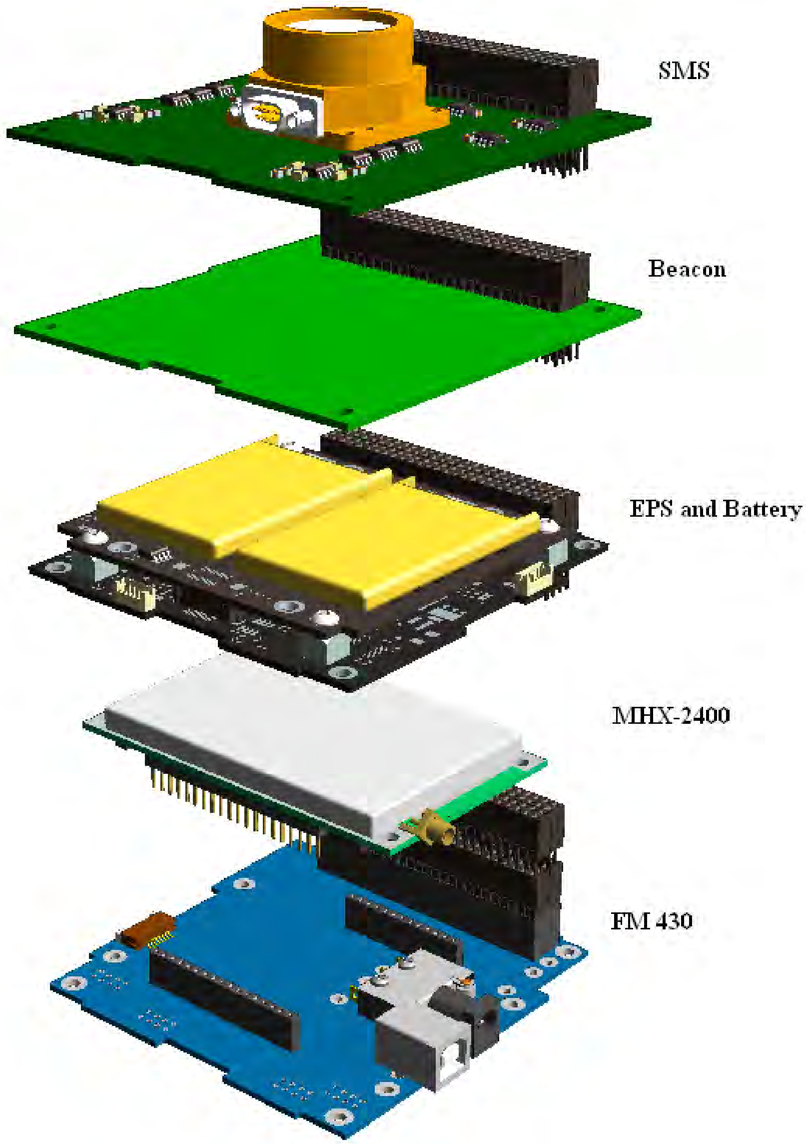

Figure 3. Break-Out of the NPS-SCAT Stack, from [4]

a. Pumpkin FM430 Board

The Pumpkin FM430 board, shown in Figure 4, controls the control and data handling (C&DH) for the satellite. Attached to this board is the MHX-2400, the primary S-band transceiver attached to the FM 430, which radiates via a patch antenna on the –Z axis of the spacecraft.

Figure 4. Pumpkin FM430 Board

b. Clyde Space EPS and Battery

The Clyde Space EPS and battery board, shown in Figure 5, accept the power from the solar power panels, manage the storage to and draw of the power from the batteries, and supply the 3.3 V, 5.0 V, and unregulated battery bus voltages for the satellite. The EPS utilizes two Varta Li+ batteries in series for a total of 10.25 watt-hour (W-hr) capacity. Communication with this board over an inter-integrated circuit (I2C) bus provides status of the power bus as well as voltages and currents of solar panel strings.

Figure 5. Clyde Space EPS and Battery

c. Beacon Board

The beacon board, shown Figure 6, is a radio transceiver board built by Cal Poly student Brian Tubb with software from Sean Fitzsimmons, which contains the secondary transceiver, the UHF beacon, and receiver. The beacon radiates via a deployable half-wave dipole antenna on the +Y-axis of the spacecraft. The stowed antenna is shown in

Figure 2 on the front face of NPS-SCAT. The antenna comprises two pieces of piano wire cut to the proper length, stowed using fishing line. Once in orbit, a piece of nickel-chromium alloy wire (nichrome) will melt the line, releasing the antenna, shown schematically in Figure 7.

Figure 6. NPS-SCAT Beacon Board Built by Brian Tubb and Sean Fitzsimmons

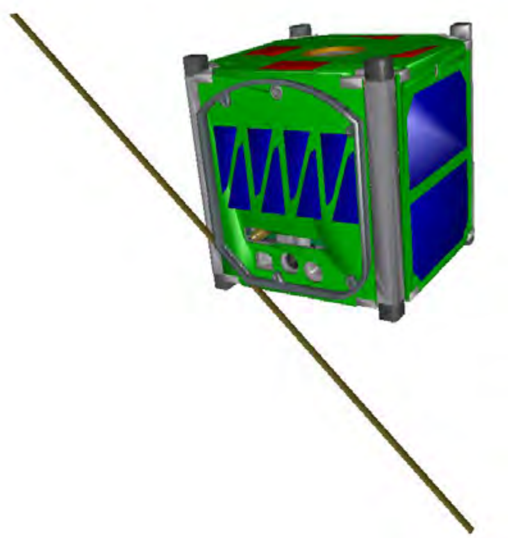

Figure 7. NPS-SCAT with Deployed Beacon, from [4]

d. Solar Measurement System

The solar measurement system (SMS board), as seen in Figure 8, is the NPS-developed payload for the satellite. Designed and built by Robert Jenkins, this board takes the inputs from the center-mounted Sinclair Sun Sensor SS-411, the local temperature sensors mounted near the solar cells, and the ESP (experimental solar panel).

Using these, it generates I-V (current—voltage) curves that quantitatively measure the performance of the solar cells over time. Knowing the sun angle allows correction of law of cosines for solar illumination.

Figure 8. SMS Board, from [4]

e. Experimental Solar Panel

The experimental solar panel (ESP board), seen in Figure 9, serves as the +Z axis of the spacecraft. It is a structural wall to which are mounted the four solar cells whose performance will be evaluated. Each is a commonly used solar cell for CubeSats. The SMS will test the cells two at a time.

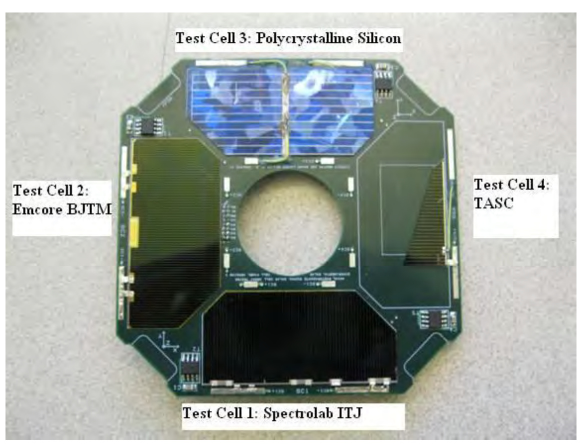

Figure 9. ESP

Test Cell 1 is a Spectrolab Improved Triple Junction (ITJ) with coverglass with 26.8 percent efficiency [5]. This type of solar cell is used on NPS-SCAT's +X, -X, and -Y surfaces. Test Cell 2 is an EMCORE Triple-Junction with Monolithic Diode (BJTM) with the highest efficiency of the solar cells chosen for this experiment at 28 percent [6]. This type of solar cell was used for the Radio Aurora EXplorer (RAX) [7], launched in November 2010. Test Cell 3 is a polycrystalline silicon [8] solar cell with 16.2 percent efficiency and is a first-generation solar cell commonly used for terrestrial purposes. Test Cell 4 is a Spectrolab Ultra Triple Junction (UTJ) Triangular Advanced Solar Cell (TASC) without cover glass with 27 percent efficiency [9]. This type of cell is also used on the –Z and +Y surfaces of NPS-SCAT for power generation.

f. Pumpkin 1U Structure

The 1U, shown in Figure 10, aluminum structure dimensions are essentially 10cm x 10cm x 10cm. The strict adherence to size is the requirement of the launcher, the Poly Picosatellite Orbital Deployer (P-POD). This was the vessel that was originally planned to house NPS-SCAT during launch and eject it into orbit. Each side of NPS-SCAT shall be 100.0±0.1mm wide and its height shall be 113.5±0.1mm tall. Solar panels, for example, shall not exceed 6.5mm normal to the surface of the 100.0mm cube [1]. Any component beyond these limitations could cause the CubeSat to become caught in the launcher and potentially cause the other CubeSats in the P-POD to fail deployment as well.

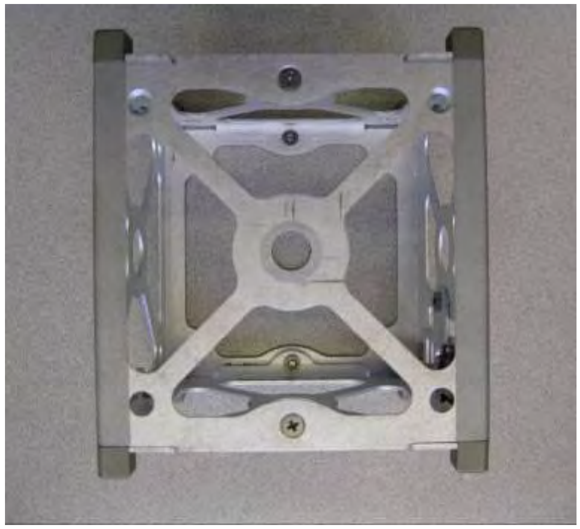

Figure 10. Pumpkin 1U CubeSat Structure

B. THESIS OBJECTIVE

This thesis will focus on the EPS, vibration testing, and integration of NPS-SCAT as a satellite. Previous student theses dealt primarily with developing the engineering design unit (EDU). The focus has now shifted to the flight version.

For the EPS, a battery capacity test was performed in order to create a state-of-charge (SOC) table. This table will be used to determine the health of the EPS while in orbit. A power budget analysis was performed for the flight batteries to determine if they are suitable for use.

NPS-SCAT, 26 other CubeSats, and STPSat-3 (Space Test Program Satellite-3) launched on November 20, 2013 as part of the ORS-3 (Operational Responsive Space-3) mission, which included eleven CubeSats from the Experimental Launch for Nanosatellites IV (ELaNA IV) mission. NPS-SCAT survived vibration testing, to ensure that NPS-SCAT will survive the launch vibration environment.

For integration, the storage of the deployable antenna and the preparation for the space environment are evaluated. These evaluations are a lessons learned for future NPS space missions.

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II. FLIGHT UNIT TESTING

A. BATTERY TESTING

The initial testing for the EPS was done on the EDU using the COTS Clyde Space Version One EPS. It was discovered during storage capacity testing that this EPS had a flaw. Under no load and with the separation switch open, the ideal battery should be isolated and have no leakage current. In actuality, the measured leakage current was about one milli-amp on a Version One EPS.

The battery has a nominal capacity of about 10.25W-hr at room temperature, or about 1250 mAh. With a leakage current of 1mA, the battery would be fully drained in about a month or so. This is unsatisfactory because there typically exists a period of months between delivery of a CubeSat and its launch. If the battery was fully drained this could have permanent damaging effects to the chemistry of the battery making it unable to recharge. The battery is critical for periods of high power stress such as during eclipse and periods of communication with the ground station.

1. Clyde Space EPS Version Two

Since the Version One EPS has an undesired leakage current, a number of fixes could be implemented to prevent this. The simplest is to use the Clyde Space Version Two EPS. The two EPSs are identical in terms of size, mass, and appearance. As shown in the Figure 11, the Version Two EPS utilizes an ideal diode on the solar cell array-charging path.

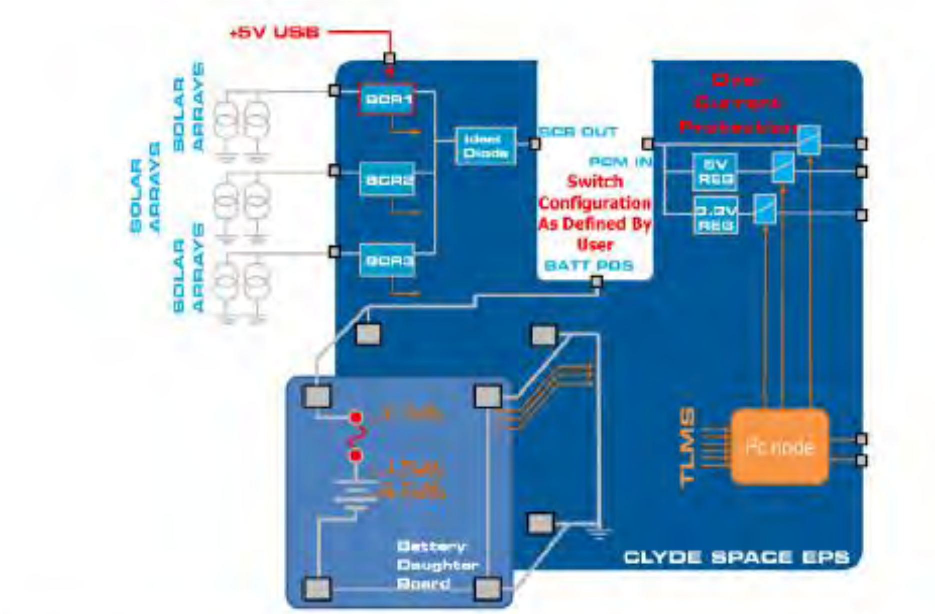

Figure 11. Clyde Space EPS Version Two

The measured leakage current in the version two EPS was 9.5µA, a factor of a hundred better than the Version One EPS. The benefits of this lower leakage current include fewer charging cycles and much longer storage time.

Other changes between the versions include the solar array battery charge regulators (SA BCRs). The X-axis and Y-axis BCRs have been switched with the effect being a minor change in-flight software to appropriately order the data fields.

2. Battery Capacity Testing

NPS-SCAT utilizes Li-ion batteries for energy storage. There are many variables that affect Li-ion battery storage capacity but the most significant are temperature, discharge current, and number of charge/discharge cycles [10]. A test of the flight batteries' 10.25W-hr capacity was performed to determine the deviation from the nominal.

At 20 degrees C, NPS-SCAT's average power dissipated under normal on-orbit operations is about 1W which equates to 125mA of discharge current, at a maximum voltage of 8V [11]. From Table 1, the discharge rate is ~C/10. The conditions for this 1W

load would be for typical operations, supplying power to the FM430 and the EPS. The battery under these conditions would have an ideal discharge curve as seen in Figure 12.

T (°C)	Discharge Rate and (measured capacity (Ah))				
40	C/15 (1.437)	C/10 (1.435)	C/5 (1.283)	C/2 (1.208)	C (1.171)
20	C/15 (1.501)	C/10 (1.430)	C/5 (1.276)	C/2 (1.226)	C (1.145)
0	C/15 (1.358)	C/10 (1.294)	C/5 (1.161)	C/2 (0.716)	C (0.182)
-20	C/15 (1.055)	C/10 (0.914)	C/5 (0.568)	C/2 (0.044)	C (0.026)

Table 1. Capacity for One Battery Cell at Different Temperatures and Discharge Rate, from [12]

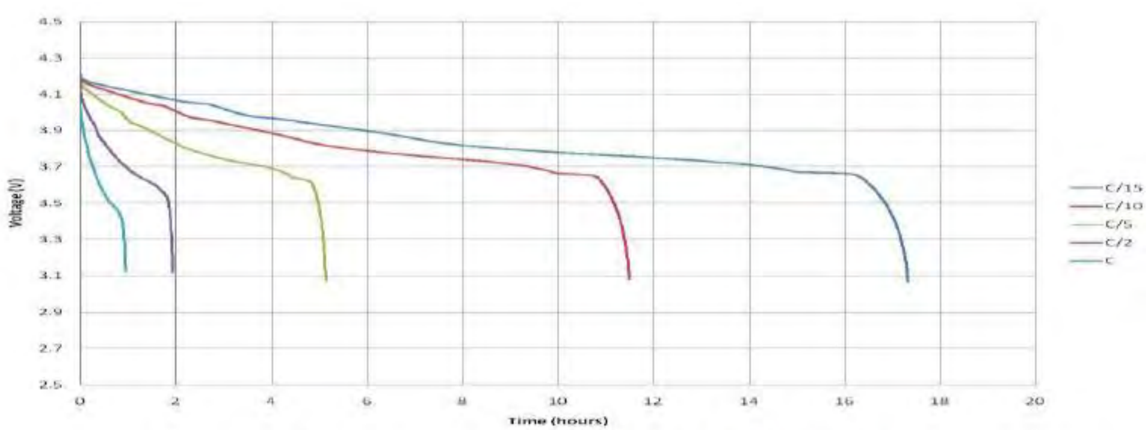

Figure 12. Capacity Comparison at Different Discharge Rates at 20°C, from [12]

A depth-of-discharge (DOD) test was conducted for batteries, CS 01189/90, to measure the storage capacity of the flight battery. Ideal conditions for the start of the DOD test would be to start from no charge and then apply a 0.2 A charging current for 6 hours to its full capacity of 1.24 A-hr. This would give a depth-of-charge (DOC) of 96.8 percent. DOC is the percent of total battery capacity stored during a charge period [10]. It was tested on 17 June 2011. The temperature of the room was a constant $20°C$. The initial charge current at 7.444V was 229 mA. The charge lasted four hours. Measured capacity was 1.08 A-hr which gives 84.8 percent DOC.

The results of the DOD test are shown in Figure 13. During this test, only the quiescent load was present and power was constant. The initial discharge current at 8.207V was 131mA. The final discharge current at 6.459V was 149mA.

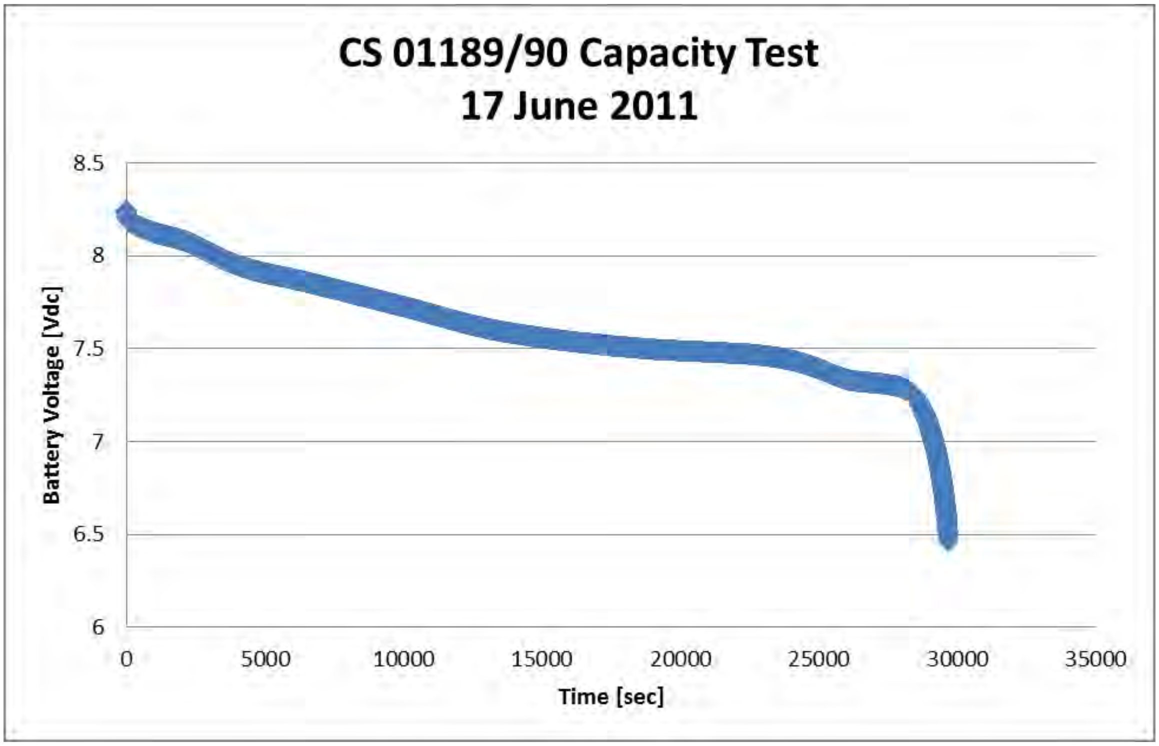

Figure 13. CS 01189/90 Battery Discharge at 1.3A

Typical discharge rates for NPS-SCAT range from about 125mA to about 150mA, dependent on the voltage level, because of the constant 1Watt load in orbit. In order to maintain constant power (P), the EPS will make up the difference in voltage (V) with current (I).

$$\overset{\leftrightarrow}{P} = \overset{\downarrow}{V} \times \overset{\uparrow}{I} \tag{2.1}$$

This is significant because the battery discharge test will not lineup perfectly with Figure 12. According to the battery specifications, the battery should have lasted about 11 hours. The test showed that CS01189/90 lasted for 8.3 hours, which makes sense because the discharge current was higher than the theoretical 125 mA. It started at 131 mA and steadily rose to 149 mA.

Since power was constant throughout the test, battery current and time were used to sum the total capacity in Amp-hrs. Once the total was determined, the state-of-charge (SOC) percentages were calculated from the total capacity. At those percentages, the battery voltage was identified and recorded in Table 2. Because capacity is not linearly correlated with battery voltage, SOC is the best way of determining how much energy is stored in the battery at any given time. SOC provides a linear gauge for battery capacity.

SOC [%]	Battery Voltage [V]
100	8.207
90	8.025
80	7.879
70	7.771
60	7.655
50	7.562
40	7.509
30	7.480
20	7.445
10	7.318
0	6.459

Table 2. SOC for CS 01189/90 at 20°C

The outputs from the Clyde Space EPS include battery voltage, current, direction of current, and EPS temperature. As stated previously, temperature and discharge current affect capacity. From the outputs, the SOC can be approximated based on the voltage and temperature. SOC will determine the relative health of the power system of NPS-SCAT on orbit.

Full capacities of the battery were derived from Table 1 at varying temperatures at the C/10 rate; 1.430 Ah at 20 degree C, 1.294 Ah at 0 degree C, and 0.914 Ah. First, the SOC intervals were calculated. Next, the voltages were mapped accordingly for each of the temperature curves. Then, constant SOC lines were added to aid in a temperature variable environment. 3.1 volts was the zero capacity reference point and 4.15 volts was the maximum capacity reference point. Data points were plotted at 0.2 volts intervals and then a linear best fit was applied between points. This introduces some error as above 3.9

volts the capacity will be over-estimated while between 3.7 volts to 3.5 volts, the "knee" in the curve, the capacity will be under-estimated. A linear approximation between the different temperature curves has been added at 10 percent intervals of SOC for ease of reference. SOC is calculated for multiple temperatures in Table 3. It is important to note that the NPS-SCAT battery utilizes two batteries in series so all voltages shown in Figure 14 are half of the total EPS voltage.

SOC [%]	-20°C [V]	0°C [V]	20°C [V]
100	8.3	8.3	8.3
90	7.56	8.0	8.14
80	7.28	7.8	8
60	7	7.62	7.76
50	6.9	7.54	7.68
40	6.8	3.732	7.6
20	6.6	7.2	7.42
10	6.4	7.06	7.2

Table 3. Nominal Battery Capacity SOC Voltages at -20°C, 0°C, 20°C

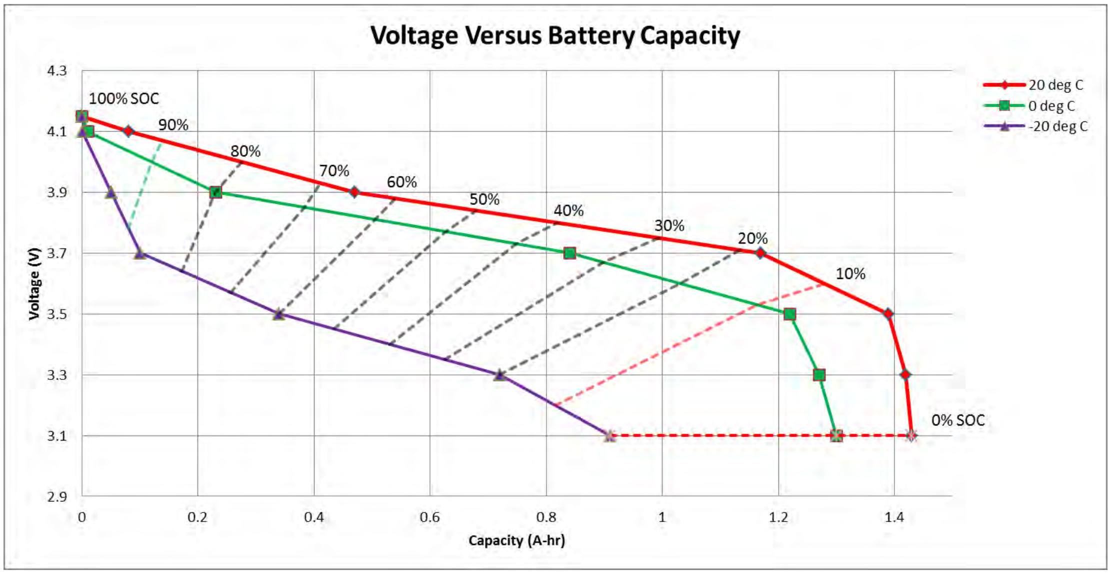

Figure 14. Temperature Versus Battery Capacity

Table 3 shows the SOC for one cell and all calculations for NPS-SCAT will be double the value on this figure. Once in orbit, the ground team can use Figure 13 or Table 3 to determine the SOC of NPS-SCAT on orbit.

While in storage, awaiting final integration, the battery voltages should be checked periodically, approximately every month. Checkers should be aware of the typical battery curve and the steep drop-off below 7.30V. The battery should be charged if below 7.40V to the maximum storage capacity of 7.60V in accordance with the charging procedures [13].

3. NPS-SCAT Power Budget

A power budget analysis was performed to determine if the NPS-SCAT is self-sustaining in its intended orbit. This analysis quantitatively compares the expected power storage capacity with the expected power consumption.

To calculate the period (T) of an orbit in hours the function,

$$T = \frac{2\pi\sqrt{\frac{r^3}{\mu}}}{3600} \tag{4.1}$$

was used. [14] μ is the constant equal to 398600 km^3/s^2. The equation, [10]

$$T_{eclipse} = \frac{T\cos^{-1}\left(\frac{\cos\rho}{\cos\beta}\right)}{\pi} \tag{4.2}$$

was used to determine the time the satellite would be in eclipse. ρ is the angular radius of the orbit and can be found by the equation [10],

$$\rho = \sin^{-1}\frac{R_{Earth}}{Altitude + R_{Earth}} \tag{4.3}$$

where β is the subsolar point and was chosen to be the worst case of zero radians. At this point the eclipse is longest and would be the most stressing eclipse possible.

At the time of this evaluation, SCAT's orbit parameters were expected to be 350 km altitude with a 51.6 degree inclination instead of the 500 km altitude and 40.5 degree inclination it became. The pre-flight analysis was for an International Space Station (ISS) reference orbit. The results are still valid because the calculated orbit is more stringent on power than the actual orbit into which NPS-SCAT was launched. At the lower altitude, NPS-SCAT would spend more time in eclipse and less time in the sun; more time consuming energy and less time storing energy. Table 4 shows the orbit times when the satellite is in eclipse and in sun.

Altitude	350 km	500 km
Orbit Period	1.53 hr	1.58 hr
Eclipse Time	0.61 hr	0.60hr
Time in Sun	0.92 hr	0.98 hr

Table 4. Orbit Eclipse and Sun Times

Table 5 shows the nominal performance of NPS-SCAT during a worst case beta orbit. The suggested minimum SOC for the battery is 80 percent [12]. The energy available (E_{SC}) is based on the 54cm^2 solar cell area (A_{SC}) at an efficiency (η) of 27 percent [14]. S is the solar flux constant equal to 1420W/m^2.

$$E_{SC} = A_{SC} \times S \times \eta \times T_{Sun} \tag{4.4}$$

The quiescent load (P_Q), 0.25 W, is the power consumed during normal flight with no communications. This load powers the FM430 and the C&DH with a processor speed of 750 kHz. The quiescent load will use 0.38 W-hr given the orbit period.

$$P_Q = P_{FM430} + P_{EPS} \tag{4.5}$$

$$P_Q = \lfloor (V_{5V} \times I_{5V}) + (V_{3V} \times I_{3V}) \rfloor + (V_{EPs} \times I_{EPS}) \tag{4.6}$$

$$P_Q = \left[(5V \times 1.1mA) + (3V \times 3.7mA)\right] + (7.5V \times 31.07mA) = 0.25W \tag{4.7}$$

Equation 4.7 uses the measured quiescent currents from each EPS voltage supply.

A nominal power budget for NPS-SCAT is shown in Table 5. The NPS-SCAT load was determined from the largest power consumers, the communication transceivers. In a given orbit, there are 5 minutes of MHX-2400 communication which gives a 5.5 percent duty cycle for 0.28W-hr energy used. In a given orbit, the UHF beacon has one 5 minute link in addition to 18 additional identity transmissions lasting 12 seconds which gives a duty cycle of 9.5 percent for 0.11W-hr energy used. When this energy use is added to the quiescent energy used, the total NPS-SCAT Energy Load is 0.77 W-hr.

Parameter	-20°C	0°C	20°C
Initial SOC [80%]	4.14 W-hr	7.78 W-hr	8.73 W-hr
Energy Available	1.47 W-hr	1.47 W-hr	1.47 W-hr
Quiescent Load	0.25 W	0.25 W	0.25 W
Energy Used Per Orbit	0.38 W-hr	0.38 W-hr	0.38 W-hr
SCAT Load	0.51 W	0.51 W	0.51 W
SCAT Energy Load	0.77 W-hr	0.77 W-hr	0.77 W-hr
SOC after Eclipse with SCAT Load	3.83 W-hr / 74%	7.48 W-hr / 77%	8.58 W-hr / 77%
SOC after one orbit w/ NPS-SCAT Load	4.45W-hr / 86%	8.09 W-hr / 83%	9.04 W-hr / 83%

Table 5. SCAT Nominal Power Budget

Table 5 shows that if the SOC at the beginning of eclipse is 80 percent, the resultant SOC out of eclipse is 74 percent in the worst temperature case of -20 degrees C. It is assumed that NPS-SCAT is actively communicating with the groundstation during the eclipse. Table 5 also shows that if the SOC at the beginning of an orbit is 80 percent, at the conclusion of one orbit, the SOC is greater than the beginning 80 percent. The result of this power budget is good because even with the worst case beta orbit, the satellite should maintain a surplus of power. It has a slow rate of charge about 3 percent per orbit.

4. Worst Case Scenario

A reoccurring problem during the testing phase has been an inconsistent I2C bus. This inconsistency is noted by temperature sensors displaying the failure signal of "-0.1." The likely cause is that there is under sampling by the processor. I2C busses typically are required to be running at a minimum of 10 kHz, but NPS-SCAT's I2C bus is running at 6 kHz due to the speed used by the microprocessor. In the previous processor configuration, the processor was clocked off of the digital oscillator which is temperature dependent. A possible solution was to run the processor off the crystal, which is more stable and less temperature dependent. The processor speed also increased from 750 kHz to 7.3278MHz, improving the reliability of the I2C bus. However, the power budget was affected because the faster processor required much more power. The average operating mode for the microprocessor is low power mode 3 (LPM3) because it uses less power by turning off the internal microprocessor components unnecessary to maintain while sleeping in between active processing cycles. This author proposes a change in the operating mode to the active mode to improve the reliability of the I2C bus. This is the worst case operating mode because the current draw would be 9 times greater, raising the quiescent load from 0.25W to 0.31W.

The FM430 has a 1mA nominal current draw. [14] The proposed change would affect the 3.3V bus current draw from 3.7mA to 7.0mA. The EPS version 2 uses 0.23W

with no load and the FM430 5V and 3.3V buses use 0.01W and 0.02W, respectively. The LPM3 quiescent load is 0.25W. The quiescent load at the higher clock speed increases to 0.26W.

Table 6 shows the overall worst case possible. This case has the worst beta angle as well as an average tumble rate of 0.03 rev/ min [11] (~0.2 degrees / sec) and is solely in the Active Mode with a maximum 7.3278MHz clock speed derived from the crystal. The NPS-SCAT energy load in this worst case scenario is 0.79 W-hr, when the same communication requirements as in the previous scenario, 0.11 W-hr, are included.

Parameter	-20°C	0°C	20°C
Initial SOC [80%]	4.14 W-hr	7.78 W-hr	8.73 W-hr
Energy Available	0.72 W-hr	0.72 W-hr	0.72 W-hr
Quiescent Load	0.26 W	0.26 W	0.26 W
Energy per orbit	0.40 W-hr	0.40 W-hr	0.40 W-hr
SCAT Load per Orbit	0.79 W-hr	0.79 W-hr	0.79 W-hr
SOC after Eclipse	3.82 W-hr/ 74%	7.47 W-hr/ 77%	8.41 W-hr/ 77%
SOC with NPS-SCAT Load after one orbit	3.66 W-hr/ 71%	7.30 W-hr/ 75%	8.25 W-hr/ 76%

Table 6. Power Budget of Nominal Battery with Worse Case NPS-SCAT Load and Tumble

In each of these scenarios, the SOC after one orbit is less than the previous orbit. This indicates that if NPS-SCAT continues to operate in this mode under these conditions there is a potential to cause a flight failure. The difference between Table 5 and Table 6 can be traced to the power produced.

With a worst case 9 percent reduction of SOC per orbit, the battery would last 9 orbits. Coincidently, this is the number of orbits NPS-SCAT will do in about a half of a day at an altitude of 350km. Efforts should be made to ensure the worst case is not realized. The factors of tumble rate and beta angle are unchangeable and must be taken as a risk. The factors of clock speed, power mode, and communications duty cycles are manageable. More analysis of the I2C bus processing must be performed to determine if changing the operating mode is worth the risk of potentially having more reliable data at the cost of more power. The power budget analysis has proven that NPS-SCAT is self-sustaining, but before it can be in orbit, it must survive the launch environment.

B. VIBRATION TESTING

Vibration testing is performed to ensure the safety of the launch and the other satellites in the launch vehicle. This is a risk mitigation technique and is performed on every spacecraft large or small. Vibration testing is performed by securing the satellite to a shaker table. The purpose is to determine if the satellite can withstand the launch vehicle acoustics and engine rumble. [10] The frequency and intensity of the vibration is determined by the testing standard. NASA General Environmental Verification Standard (GEVS) testing standard was chosen about three years prior to the actual flight because the launch vehicle had not been selected. GEVS testing levels are designed to encompass most of the common launch vehicles. At the time of this testing, NPS-SCAT was to be launched on the ELaNa IV mission on a Falcon 9 for which GEVS would have been adequate. The flight unit was tested for defects under the supervision of Dan Sakoda, using procedures developed by Marissa Brummitt, and with the assistance of Adam Hill, NPS-SCAT Program Manager.

1. ELaNa IV Random Vibration Levels

For initial qualification, the satellite was tested to the GEVS standard, a baseline NASA standard [15]. However, once the launch vehicle was determined the standards for qualification changed. Figure 15 shows how the two curves are similar. However, the ELaNa IV levels have much more energy in the lower frequencies. These are particularly large, almost violent shakes. The vibration testing levels are displayed in Table 7.

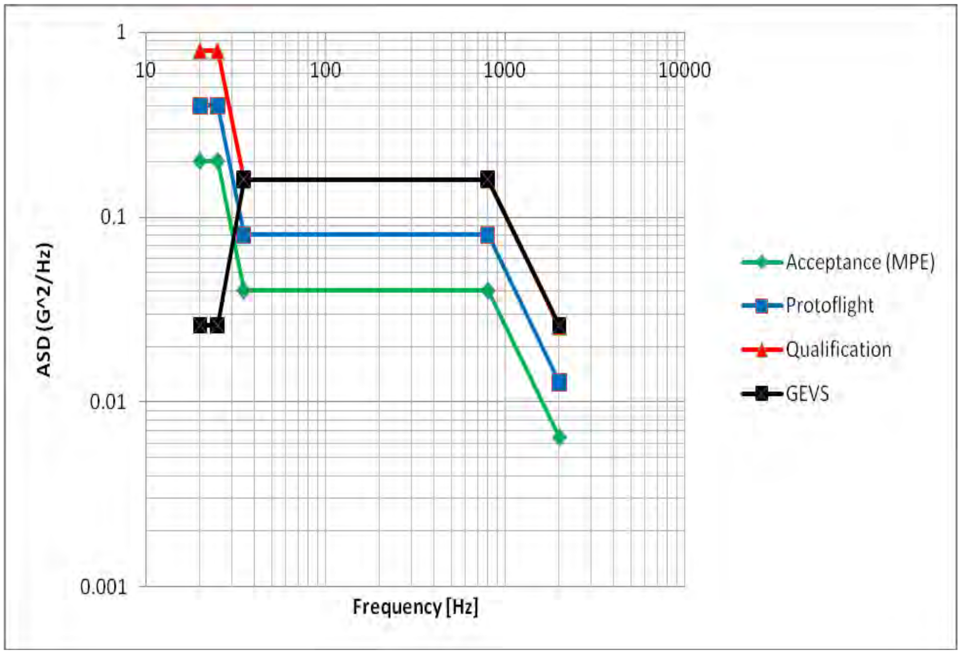

Figure 15. Random Vibration Test Levels for ELaNa IV Versus GEVS

	Acceptance (MPE)	Protoflight	Qualification	GEVS
Freq (Hz)	**ASD (G^2/Hz)**	**ASD (G^2/Hz)**	**ASD (G^2/Hz)**	**ASD (G^2/Hz)**
20	0.2	0.4	0.8	0.026
25	0.2	0.4	0.8	0.026
35	0.04	0.08	0.16	0.16
800	0.04	0.08	0.16	0.16
2000	0.00644	0.0128	0.0256	0.026
Overall Grms	7.2	10.17	14.39	10
Duration	60 secs	120 sec	180 sec	60 sec

Table 7. Random Vibration Test Levels for ELaNa IV Versus GEVS

2. Vibration Test Results

NPS-SCAT was submitted to the random vibration test levels identified in Table 7. Then it was subjected to a Sine Sweep Vibration Test to determine natural frequencies of the structure. The results are examined in each axis. These tests are used to determine the survivibility of NPS-SCAT in launch.

a. Random Vibration Test Results

In Figure 16, the blue line is the data from the X-axis. The green line is the data from the Y-axis. The orange line is the data from the Z-axis. The test did not show any particular modes and each axis matches the vibration profile. NPS-SCAT shows no signs of failure from the test. The largest response is 14g at 80Hz.

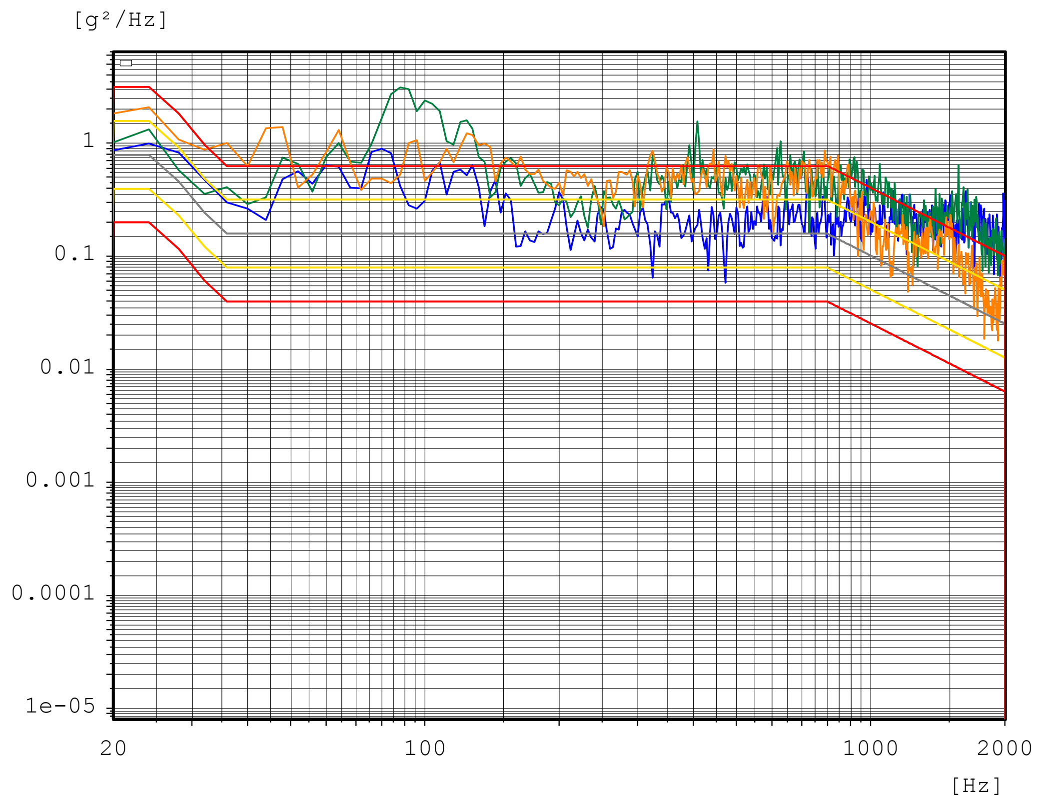

Figure 16. ELaNa IV Random Vibration Levels Test Results

b. Sine Sweep Results

In Figures 17 through 19, the blue line represents the sine sweep before the random vibration test and the green line represents the sine sweep after the random vibration test. Table 8 shows the Sine sweep results for each axis. A large change in modes would indicate a failure of the test [15].

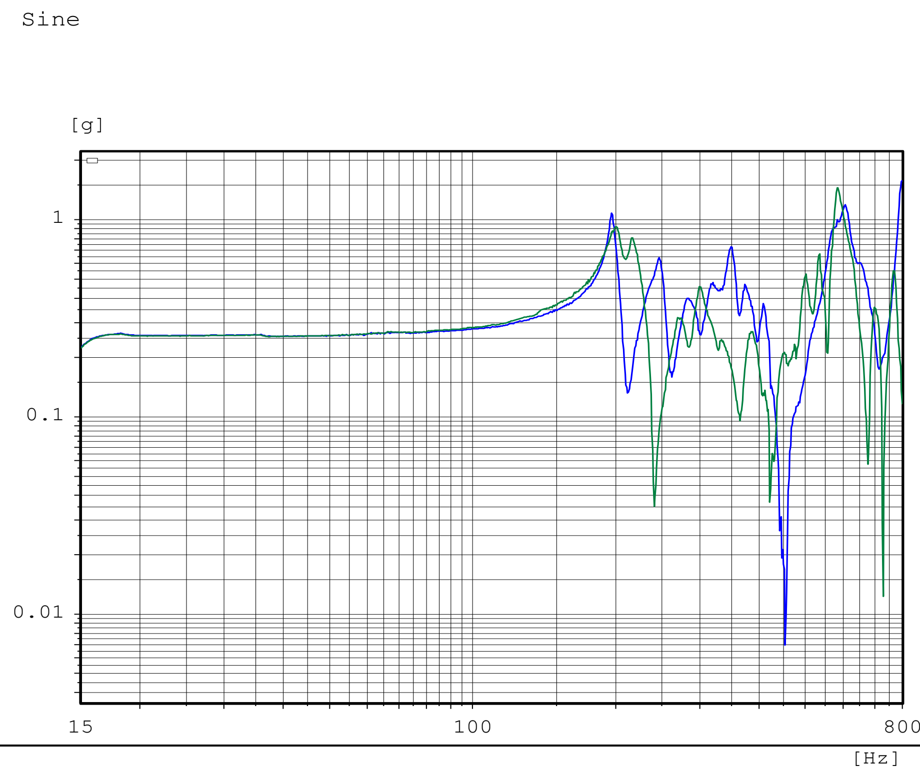

Figure 17. Pre and Post Sine Sweep Comparison X-Axis

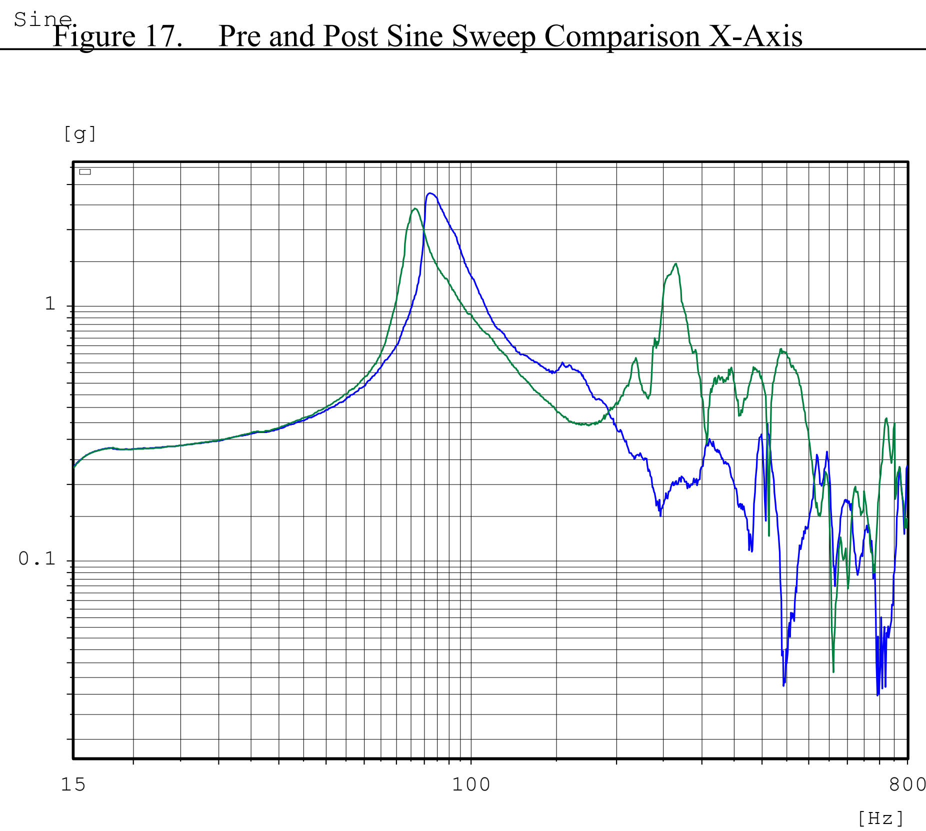

Figure 18. Pre and Post Sine Sweep Comparison Y-Axis

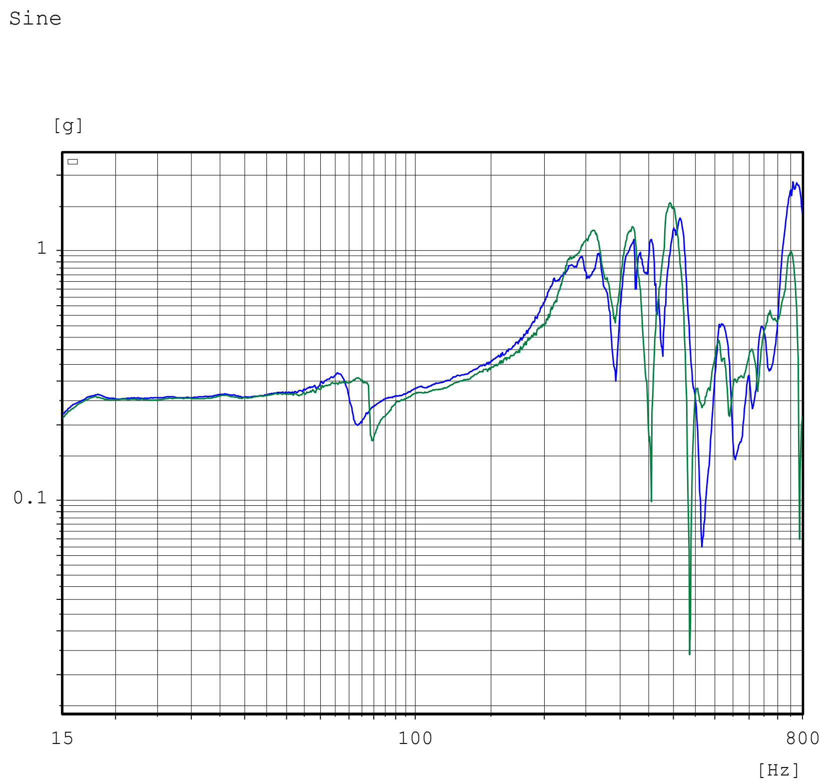

Figure 19. Pre and Post Sine Sweep Comparison Z-Axis

Parameter	X-axis		Y-axis	Z-axis
Pre-sine Freq [Hz]	196	607	83	415
Pre-sine Amp [g]	1.08	1.20	2.78	1.35
Post-sine Freq [Hz]	198	584	77	392
Post-sine Amp [g]	0.89	1.46	2.42	1.56
% Difference	1.02%	3.79%	7.23%	5.54%
Q	21.78	26.39	7.55	12.58

Table 8. Sine Sweep Test Results

The percent difference is a measure of the survivability of the craft after the random vibration test. If a component had changed during the test it would be noted by a significant change in the frequency of the modes or the number of modes the profile has. A change is considered significant if the percent difference exceeds 20 percent. All of NPS-SCAT's modes are well within this quality check.

The quality factor, Q, is a dimensionless parameter that describes how under-damped an oscillator is [16]. Each of the NPS-SCAT modes have a low Q and a high dampening value which means that the energy is dissipated quickly and it will not resonant for a long time, which is desirable.

NPS-SCAT has been found suitable for the launch environment. This concluded the laboratory testing phase that determined overall suitability of NPS-SCAT in launch and while in orbit. Before it can be launched, it must be packaged for launch, known as integration.

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III. NPS-SCAT FLIGHT PREPARATION AND INTEGRATION

This section evaluated the final preparations made for NPS-SCAT's integration. Conformal Coating is necessary to protect components exposed to the harsh space environment. The best application was determined. Additionally, potential hardware issues were identified with the deployment mechanism for the beacon antenna.

A. CONFORMAL COAT

A brush method and a syringe method were chosen to apply the Conformal Coat. These methods were compared on ease of application and appearance. This section will provide lessons learned for future applications for NPS spacecraft.

1. Brush Versus Syringe

The brushes used in this procedure were Testors 8706 paint brushes in a set of 3; a pointed, a flat, and a one-quarter inch wide with Nylon shed-proof bristles. The syringes used were of 14, 16, and 20 gauge one and one-quarter inch length with 2 cc volume available. The conformal coat used was CV- 1152 conformal coat.

One set of solar panels was coated using the brushes while the other set of solar panels was coated using the syringes. The designations of backup (B/U) and flight were not made prior to the experiment. Instead the distinction was made after the results were evaluated. As such, there was no previous disposition to which technique would be better. Better is defined by ease of application and overall appearance. In hindsight, the solar panels should have been covered to prevent conformal coating material from covering some of the solar panels. The effect of covering small areas of the solar panels with conformal coating could have a negative impact for power generation.

Both the brushes and the syringes coated the components well. The problem occurred when the brushes were used. The conformal coat got onto some parts on a few of the solar cells. The syringes provided much more control and the conformal coat stayed where it was applied. In this author's opinion, the syringes are easier to handle.

Conformal coat using syringes was determined to be the better unit and therefore designated as the flight unit. The other set of solar panels were designated as the backup (B/U).

2. Application

On the back-up flight FM430 board the coat was applied thickly over all the board. This led to the MHX pins filling with conformal coating material, rendering the board incapable of integration. The pins were cleared. The cause of this problem was identified as the gap around the pins was not large enough to allow expansion of the conformal coating material. Conformal coat expands due to its surface tension. A paper barrier around the pins would protect them from the conformal coating.

B. DEPLOYMENT HOOKS

As the secondary transceiver, the beacon board is the backup communication link, a redundant link. Lining the +Y surface are small bronze hooks that secure the deployable antenna for launch. These hooks are necessary to ensure the antennae stays inside the acceptable volume for the CubeSat. The hooks are not without their issues, as discussed below.

1. Deployment Hooks

NPS-SCAT is a compact satellite when fully integrated. NPS-SCAT has few moving parts that convert the satellite from integrated mode to flight mode. In fact it has just one deployment mechanism, the beacon antenna. Successful deployment of the beacon antenna means that the nichrome wire burns through the fishing line that holds the antenna secure. A Palomar knot is used on the beacon tip and is tied to the nichrome fixture using a rolling hitch knot. Once the tension in the fishing line is gone the spring force of the beacon antenna itself should be enough to have the antenna deploy fully to its straight position.

2. Failure Modes and Corrective Action

Tests have shown this event to have a success rate of about 50 percent. The deployment most often failed in one of three ways.

a. First Failure Mode

The first failure mode was that the nichrome wire failed to burn completely through the fishing line. One cause was that the current through the nichrome was too low, requiring replacing the resistors and the current-enabling metal-oxide-semiconductor field-effect transistors (MOSFET), shown in Figure 20. Another cause was that the fishing line was secured too close to the base of the nichrome joint. At this point the heat generated in the nichrome was more evenly dispersed over a large surface area, resulting in insufficient heat to burn the fishing line. The correction to this is to tie the knot to the center of the nichrome line. The final flight configuration was to have a small bend in the center of the wire which helped retain the knot centered.

Figure 20. Beacon Board

b. Second Failure Mode

In the second failure mode, the beacon would get caught on the retaining hooks. At either end of the antenna are loops in the piano wire, used to secure the antenna with fishing line. Upon release, these loops would most often get caught on hook 8. Hook 8 is

on the most +Z hook on the -X edge of the +Y panel. To change this, this hook was shortened to little more than a post, shown in Figure 21. This modification was first done on the EDU, to be done later on the flight boards.

Figure 21. Beacon Hook 8 Shortened

c. Third Failure Mode

In the third failure mode, the antenna loops would get caught on each other, shown in Figure 22. This is the most dangerous failure mode because the beacon indication would be a false deployment. The indication of deployment is made when the contact is lost between the beacon wire and the hook. This failure mode occurred when the 2 beacon half, -Z, was secured before the 1 beacon half, +Z. In the normal deployable antenna integration procedure, developed by Rod Jenkins, the +Z beacon half is stowed using the hooks in the +X and +Z regions of the +Y panel prior to the -Z beacon half which is stowed using the hooks in the -X and -Z region of the +Y panel. The order in which the beacon wires were secured may have been a contributing factor. This failure was a rare occurrence, having happened only once.

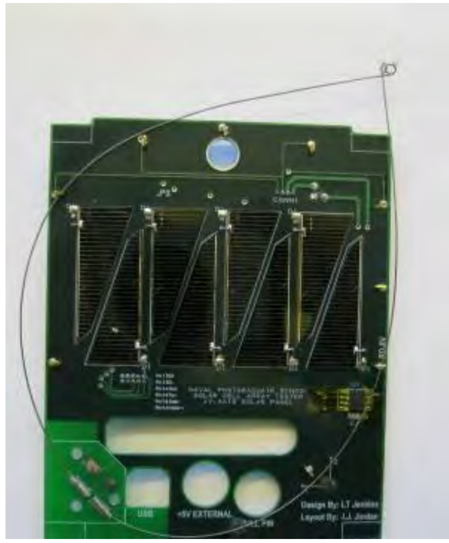

Figure 22. Worse Case Beacon Deployment Failure

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IV. NPS-SCAT IN ORBIT

A. LAUNCH NPS-SCAT

NPS-SCAT launched 20 November 2013 on the Operationally Responsive Space 3 (ORS-3) mission. It successfully deployed from the Nanosatellite Launch Adapter System (NLAS) into a low earth orbit with an altitude of 500 km and inclination of 40.5 degrees.

B. FLIGHT DATA

NPS-SCAT was able to communicate with the Cal Poly and NPS groundstations over a five day period. The data relayed is compared with the SOC Chart developed previously.

1. EPS Information

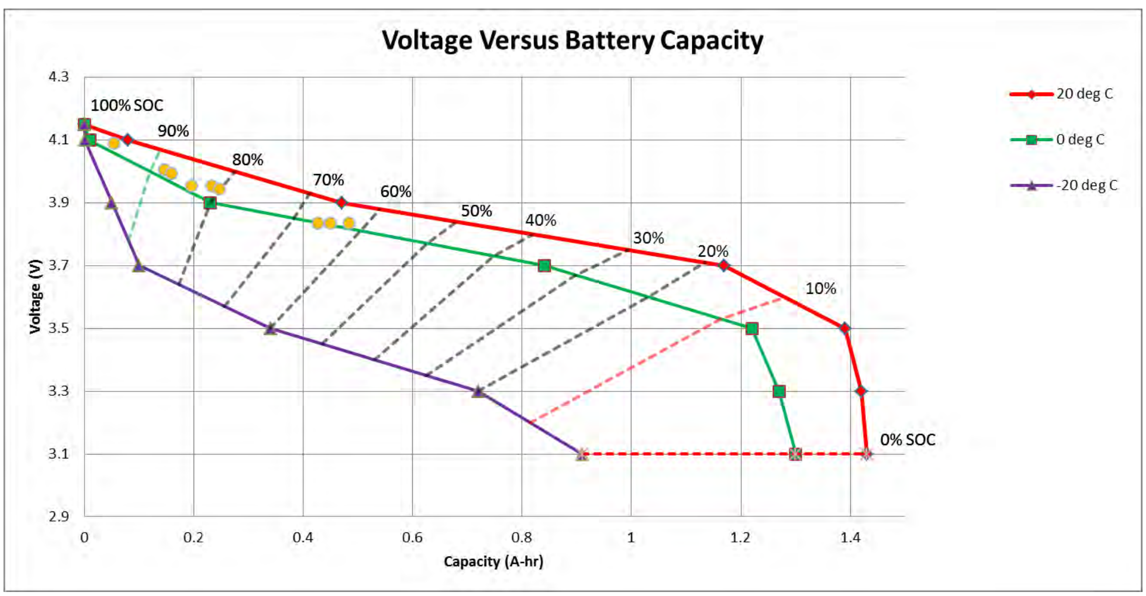

Figure 23. SOC Chart with NPS-SCAT Flight Data

The data packets that contained EPS voltage and temperature were plotted in Figure 23 and shown in Table 9. Each plotted point was placed along the 0 degrees C curve based on voltage. The 0 degrees C curve was chosen because the measured

temperatures were closest to that curve. Then, a temperature offset coefficient was added to the capacity by comparing the capacity difference between the 0 and 20 degrees C temperature lines at constant voltage. Each of the recorded temperatures is coincidently between the 0 degrees C and the 20 degrees C temperature curves.

$$Capacity_{total} = \left(Capacity_{20} - Capacity_{0}\right)\left[\frac{Temp_{Batt} - 0°C}{20°C - 0°C}\right] + Capacity_{0} \qquad (3.1)$$

Date/time	Temp_ Batt [degC]	Batt_ Volt [V]	Batt_ Cell [V]	Capacity_ 0deg[A-hr]	Capacity_ 20 deg [A-hr]	Capacity Total [A-hr]
23/0:10	1.0	7.67	3.84	0.41	0.70	0.43
23/1:15	2.6	7.67	3.84	0.41	0.70	0.45
23/3:31	5.0	7.67	3.84	0.41	0.70	0.48
24/1:28	3.6	7.91	3.96	0.16	0.36	0.20
24/3:14	7.2	7.91	3.96	0.16	0.36	0.23
24/4:50	7.2	7.89	3.95	0.17	0.38	0.25
25/1:08	5.2	8.01	4.01	0.10	0.27	0.15
25/2:44	5.2	7.99	4.00	0.12	0.28	0.16
27/3:49	9.8	8.18	4.09	0.01	0.10	0.05

Table 9. NPS-SCAT Flight Recorded Data

From Figure 23, the lowest data point has more than 60 percent SOC which occurred early in orbit as expected. Over the following days, the SOC had risen to the desired 80% SOC and even went beyond the 90 percent SOC. NPS-SCAT was self-sustaining. The power budget analysis performed is confirmed by the flight data. The change in orbit from the pre-flight ISS orbit to the flight orbit was not a significant factor in the power budget analysis.

V. CONCLUSION

A. SUCCESS OF NPS-SCAT AND FUTURE WORK

The work for this thesis was primarily done a couple of years before the final vibe testing, necessitated by the final selection of the Minotaur I launch vehicle, and integration for flight of NPS-SCAT. Final testing and integration was performed by Aaron Felt with a different CubeSat launcher, the NLAS.

NPS-SCAT certainly succeeded in its goals of teaching students about CubeSats and about real satellite development, analysis, testing, and integration. It was also at least partially successful in its planned mission. The simple fact that NPS-SCAT communicated with the ground stations is a success in itself. A success that stands above a significant portion of the other CubeSats, 27 in all, launched on the same mission.

NPS-SCAT was not a complete success in that the temperature sensors failed and the short mission did not permit the goal of characterizing degradation of the solar cells over a significant amount of time. The failure of the temperature sensors is likely due to the radiation environment affecting the external digital temperature sensors. Four temperature sensors did record data in the early data packets, but by the second day of flight all external temperatures had failed. The only temperature sensors to not experience failure were the SMS temperature sensor and the EPS temperature sensor. Due to the gradual nature of the sensor degradation, radiation is the likely cause. Radiation hardening or mitigation should be a consideration in the design of future NPS satellites. Further analysis is needed to determine which COTS components are suitable for the space environment. Another potential culprit for the I2C bus instability could be the pull down resistor. Other CubeSats using the Clyde Space 1U EPS unit saw similar I2C bus reliability issues [17]. Further research is necessary.

In conclusion, NPS-SCAT, as the first NPS student CubeSat, succeeded in important ways, but did leave room for future improvement. The CubeSat form factor, using COTS hardware whenever possible, is expected to contribute to both education and other national purposes as experience grows with this emerging technology.

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LIST OF REFERENCES

[1] S. Lee, A. Hutputanasin, A. Toorian, W. Lan, and R. Munakata, "CubeSat design specification Rev. 12," California Polytechnic State University, San Luis Obispo, August 2009.

[2] D. Sakoda, J. A. Horning, and S. D. Moseley. "Naval Postgraduate School NPSAT1 small satellite," Naval Postgraduate School, Monterey, CA, 2006.

[3] D. Sakoda. "NPSAT1 CAD model," Naval Postgraduate School, Monterey, CA, 2009.

[4] R. D. Jenkins IV. "NPS-SCAT: systems engineering and payload subsystem design, integration, and testing of NPS' First CubeSat," M.S. thesis, Dept. Astronautical Engineering, Naval Postgraduate School, Monterey, CA, 2010.

[5] Spectrolab Inc., "26.8% improved triple junction (ITJ) solar cells," Spectrolab Inc., Sylmar, CA, May 2002.

[6] EMCORE Corporation, "BTJM photovoltaic cell," EMCORE Photovoltaics, Albuquerque, NM, September 2012.

[7] J. Cutler. "The Radio Aurora EXplorer CubeSat electrical power system overview, Version 1.2," University of Michigan, Ann Arbor, MI, 2010.

[8] Hebe Corporation, "Multicrystalline silicon solar cell," Hebe Corporation, Ningbo, China, 2008.

[9] Spectrolab Inc., "Triangular Advanced Solar Cells (TASC)," Spectrolab Inc., Sylmar, CA, April 2002.

[10] J. R. Wertz, and W. J. Larson. "Space mission analysis and design," 3rd ed., Space Technology Library, Mircocosm Press and Springer, New York, 2008.

[11] L. T. Dorn, Jr., "NPS-SCAT electrical power system," M.S. thesis, Space Systems Operations, Naval Postgraduate School, Monterey, CA, September 2009.

[12] A. Strain. "Clyde space user manual: CubeSat 1U electrical power system and batteries: CS-1UEPS2-NB/-10/-20," Clyde Space Ltd., Glasgow, United Kingdom, July 2010.

[13] J. M. Fletcher. "Electrical power subsystem integration and test for the NPS solar cell array tester CubeSat," M.S. thesis, Astronautical Engineering, Naval Postgraduate School, Monterey, CA, December 2010.

[14] J. J. Sellers, W. J. Astore, R. B. Giffen, and W. J. Larson. "Understanding space: An Introduction to astronautics," McGraw-Hill, New York, 2007.

[15] M. L. Brummitt. "Development of CubeSat vibration testing capabilities for the Naval Postgraduate School and Cal Poly San Luis Obispo," M.S. thesis, Aerospace Engineering, California Polytechnic State University, San Luis Obispo, CA, December 2010.

[16] J. H. Harlow. "Electronic power transformer engineering," CRC Press, Boca Raton, FL, 2004.

[17] C. S. Brandon. "I2C and power supply/battery issues in CubeSats," Vermont Technical College, Randolph, VT, January 2014.

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